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DIRECTIONAL GRINDING HARDNESS OF QUARTZ BY PERIPHERAL GRINDING*

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Recently Giardini (1) and Giardini and Conrad (2) have successfully studied the directional grinding hardness of strontium titanate and silicon single crystals by cutting oriented disks and grinding the periphery of the disks in a lathe. An outstanding feature of the method is that information on the symmetry of hardness vectors is quickly obtained from the measurements. It occurred to the writers that the peripheral grinding method might be used to verify experimentally the hypothesis that grinding hardness is a non-centrosymmetric property of crystals. Quartz was chosen for the study as being most suitable from the standpoint of availability and mechanical properties, among non-centrosymmetric crystals. At the outset, quartz is not ideal for the purpose because of the near isotropy of its other physical properties. Quartz possesses a poor to distinct prismatic cleavage $\{10\cdot 0\}$ and a similar pair of rhombohedral cleavages $\{10\cdot 1\}$ and $\{\bar{1}0\cdot 1\}$. The cleavage of quartz may be readily observed on a rough ground single crystal sphere. Reflection maxima are easily detected so that such a sphere can be accurately oriented in reflected light; the only ambiguity is that introduced by the inability of the observer to distinguish between $\{10\cdot 1\}$ and $\{\bar{1}0\cdot 1\}$. The presence of cleavage suggests a likelihood of measurable hardness variation, although the large number of cleavage planes (nine) indicates that the variations may not be very large.

The reader is referred to the paper by Giardini and Conrad (2) for a description of the method of peripheral grinding. External morphology and etch figures were used as an aid in selecting single crystal oriented disks in this study. The hand of the crystals was determined by light figures from etched surfaces and the rotation of the plane of polarization of light traveling parallel to the optic axis as described by Parish and Gordon (3).

The disks were mounted on a spindle and centered as well as possible in the lathe chuck. The chuck was divided into five degree increments which could be read at a fixed index. The centering and radial reductions were determined by means of a dial indicator. Thus the reduction of the

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radius of the disk due to grinding could be recorded for the desired angular position of the chuck (azimuth). The lathe cross feed served to locate the dial indicator and also to locate the abrasive tape against the disk for grinding.

The indicator was graduated to 0.001 inch. Readings to 0.0001 inch were estimated and are believed to be correct to 0.0003 inch. The reading of the azimuth angle is not particularly critical, but is correct to within one degree. The thickness and maximum and minimum disk diameters were measured with a micrometer graduated to 0.001 inch. Experimental conditions were essentially the same as those used in the silicon and strontium titanate studies previously mentioned.

Three disk orientations were chosen for the present study: a [00·1] disk and a disk of general orientation (zone axis; $\phi=226°$, $\rho=37°$) to investigate the non-centrosymmetric nature of the hardness and a [01·0] disk as an example of two-fold symmetry.

As a test of the validity of the method, an optically isotropic pyrex disk was subjected to a series of measurements. The initial eccentricity due to lack of perfect centering was reduced during the first grinding period. Observations after further grinding indicated that the equilibrium between eccentricity and hardness attained during the first grinding period was valid within experimental error. Thus it is reasonable to conclude that any initial eccentricity will be reduced during grinding and that variation in hardness will be the principal factor upon which differences in radial reduction will be dependent.

The reproducibility of the method was checked by making observations of the radial reductions produced by successive grinding increments. In the case of quartz, the observed relative grinding hardnesses produced by successive tests agree within 10 per cent.

Relative grinding hardness values were computed from the observed radial reductions using the following definition for relative grinding hardness (4): $RGH=K_s/K_n$ where K_s is the grinding constant for a direction of arbitrarily chosen unit hardness and K_n the grinding constant in the direction under consideration. The grinding constant $K=v/FT$, where v is the volume removed, F is the force normal to the grinding surface and T is the time of grinding.

Hardness values were computed for each ten degree increment using the largest radial reduction as the standard value for each test. Successive values for each orientation were then averaged and the standard deviation was computed.

Average relative hardness values for each disk were then determined with the above equations, using the volume removed during the entire grinding period to determine the grinding constant (K) for each disk.

This computation yielded the average hardnesses of the disks. The lowest hardness value was selected as a reference value and all hardness values were multiplied by constants which preserved the relation of the average hardness values for various disk thicknesses. These same constants were applied to the standard deviations. Adjusted standard deviations are as follows: [00·1] disk=0.063; [01·0] disk=0.025; disk of general orientation ($\phi=226°$, $\rho=37°$)=0.038.

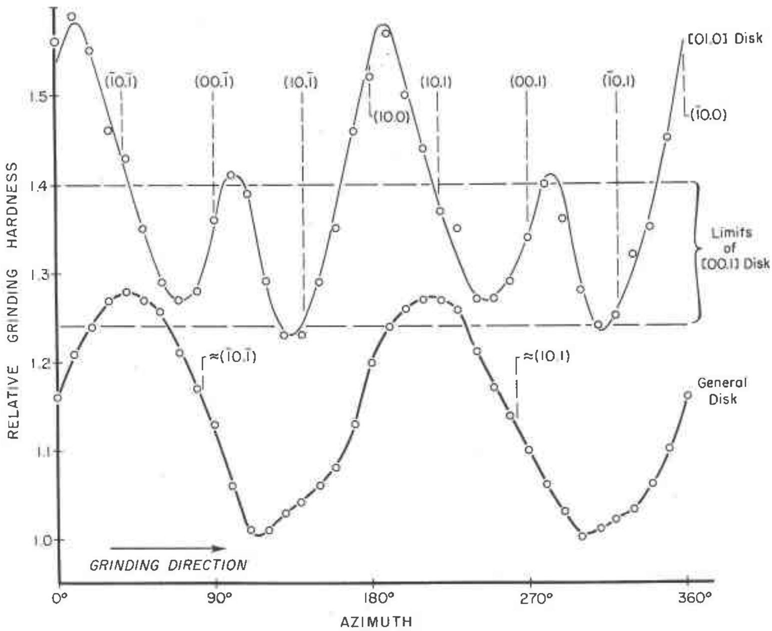

FIG. 1. Relative grinding hardness of quartz.

Figure 1 is a plot of the relative grinding hardness of the three disk orientations studied. The maximum and minimum hardness values of the [00·1] disk are plotted as dotted lines because no systematic variation of hardness compatible with the symmetry was observed. The Bravais-Miller indices of significant planes are indicated in the figure. Figure 2 is a cyclographic projection of the disks on which zero azimuths, grinding directions, and rotation directions are indicated.

The results of measurement for the [00·1] disk are not satisfactory, apparently for two reasons. First, the anisotropy is low; and second, the two disks used were ground under a very small radial force. For this reason a curve is not plotted, but rather the approximate limits of hardness for the prism zone are shown by broken lines on the figure. An improvement in technique probably would permit a reproducible hardness curve for this orientation.

The two-fold symmetry of the hardness curve of the [01·0] disk is apparent. The curve for the disk of general orientation does not approach the two-fold symmetry so closely as the former. It is apparent

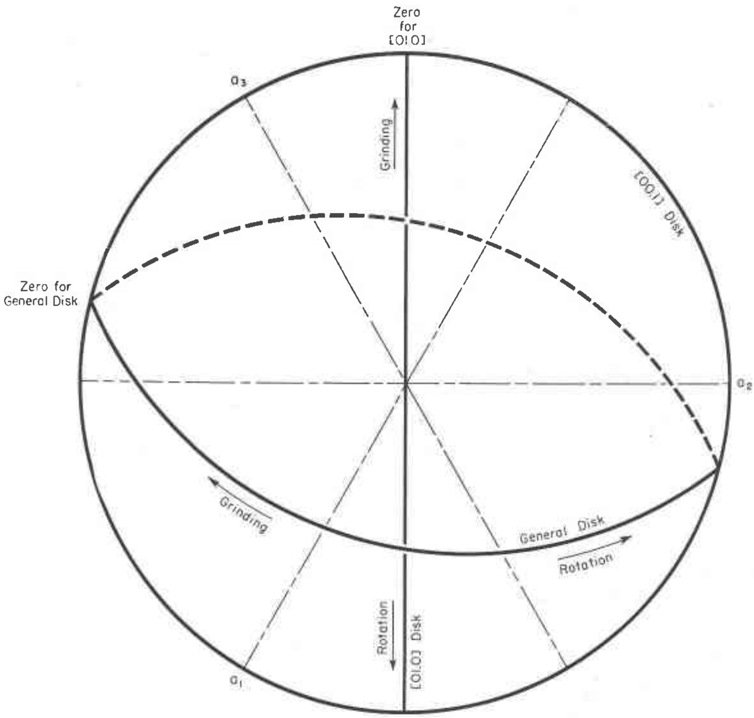

FIG. 2. Cyclographic projection of the quartz disks.

that the slight deviation from two-fold symmetry may be fortuitous and cannot be considered as significant.

It is not possible to combine the curves obtained from a series of disks to form a useful and meaningful solid of relative grinding hardness, since grinding hardness is dependent upon the orientation of the plane being ground and the direction within the plane.

It is well to consider the symmetry that the two-dimensional hardness curves would be expected to show for the possible symmetry elements of crystals. A disk whose axis coincides with an n-fold symmetry axis of rotation or rotary reflection must exhibit a hardness curve of n-fold or compatible symmetry. If the symmetry axis is an axis of rotary inversion, the relations (which can be verified easily with the aid of a stereographic projection) are as follows: if the disk axis be parallel to $\bar{2}$, $\bar{3}$, $\bar{4}$, or $\bar{6}$, the hardness variation shown by peripheral grinding of the disk must be compatible with 1, 6, 4, or 3-fold symmetry respectively.

If a disk is cut from a centrosymmetric crystal the least symmetry which can be manifest is twofold. Incidentally an important point, about which there has been some confusion, is the equivalence of hardness vectors required by a center of symmetry on sawed (or cleaved) crystal surfaces. Figure 3 illustrates a crystal which has been sawed on the stippled plane. A hardness vector H on the sawed surface of Part A is repeated by a center of symmetry as H′ on Part B.

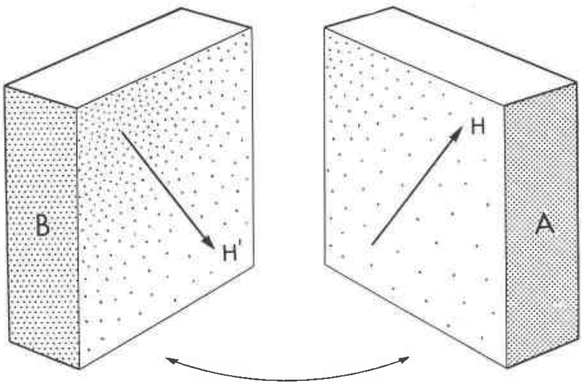

FIG. 3. Repetition of a hardness vector in a cleaved centrosymmetric crystal.

A symmetry plane parallel to the axis of the disk will reveal itself only if curves are obtained for opposite directions of disk rotation. Under such conditions the two curves will be related to each other by a line of reflection parallel to the trace of the symmetry plane.

Ideally (from symmetry considerations alone) if a sufficient number of properly chosen disks be ground, some in opposite directions of rotation, a unique crystal class determination should be possible from hardness measurements alone. Furthermore, it should be possible to distinguish between right and left enantiomorphs. Practically, this has not been accomplished. About the best that has been done is to show measurements consistent with the symmetry elements of the substance investigated.

Anisotropy (A) may be expressed by the following formula, in which H is relative grinding hardness and R is radial reduction:

$$A = \frac{2|H_1 - H_2|}{H_1 + H_2} \text{ or } \frac{2|R_1 - R_2|}{R_1 + R_2}$$

Using the maximum and minimum hardness values, quartz has an anisotropy of 0.25 for the [01·0] disk, 0.24 for the disk of general orientation, and 0.11 for the [00·1] disk. As a comparison, the anisotropy of relative grinding hardness of diamond (4) is two which is, of course, the theoretical maximum anisotropy defined by the above equation. The anisotropy of hardness of strontium titanate is 0.70 (1) and of silicon 0.26 (2). No single crystal as yet studied has displayed isotropic grinding hardness (anisotropy of zero).

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TEPHROITE FROM CLARK PENINSULA, WILKES LAND, ANTARCTICA

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In January 1957 a United States base (Wilkes Station) was established on Clark Peninsula (about 66° S, 110° E), in Wilkes Land, in connection with the International Geophysical Year. Mr. Walter Sullivan accompanied the expedition as a reporter for the *New York Times*, and while ashore at Wilkes Station he noticed a vein of black rock with a metallic sheen in the light-colored gneisses forming the bedrock of this region. He observed that the vein outcropped at several points on a ridge near the site of Wilkes Station, and that where it was exposed it was less than a yard wide. He also noticed green stains of malachite along joints in the country rocks. Mr. Sullivan collected a number of specimens and on his return to New York he gave them to the museum. Laboratory examination showed that the black vein material consisted largely of the manganese silicate tephroite. Since tephroite is not a common mineral and has not been previously recorded from Antarctica the material has been investigated in some detail.

The specimens as collected are coated with a black iridescent film with a metallic luster, evidently a manganese oxide. On fresh fracture, however, the material has a dark ash-gray color typical of tephroite; small grains of yellow spessartite are scattered through the tephroite, and occasional small patches of white barite and pink rhodonite are present.